

Metrics for In-Space Telescope Assembly Techniques

Stuart K. Stephens

NASA Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91009
818-393-7807

stuart.k.stephens@jpl.nasa.gov

Harvey J. Willenberg

Boeing Phantom Works
5301 Bolsa Avenue, Huntington Beach, CA 92647
714-372-9409

harvey.j.willenberg@boeing.com

Abstract— Reliable metrics are not yet available for choosing among human and robotic assets for space-based construction and servicing of large space telescopes. Using FAIR-DART as a reference design, we generated example event sequences for telescope assembly scenarios in enough detail to identify infrastructure assumptions and technology requirements. A systems trade among human and robotic techniques (human EVA, on-site telerobotic, ground-in-the-loop robotic, commanded or sequenced robotic, and autonomous/decision-making robotic) helped us to define key metrics in the human-robotic trade space, including quality, time, cost, and risk. Our methodology included examining representative end-member scenarios. Case A treated each step in the assembly sequence as if all other steps have no on-site human involvement, and Case B treated each step as if human EVA is already involved in all other steps. With this trade, we identified key enabling technologies and infrastructure for space-based assembly and servicing of large space telescopes.

questions of the origins of stellar and planetary systems, the search for extraterrestrial life, and the search for and characterization of Earth-like planets around nearby stars. A common theme for improvement of telescope instrument performance has been the need for larger, more precise optics. In general, larger apertures with more precise optics result in higher quality science. Space telescopes are designed for the largest practical lens structures that can be configured inside the payload envelope of existing launch vehicles, generally about 3-4 meters in diameter. The structures must survive a harsh launch environment with strong vibrational loads, which dictates massive designs with large structural design margins so that, even if the lenses filled the payload fairing, they would still be far more massive than if they could be assembled in space. This is the single constraint limiting ever higher performance devices: the inability to deliver optical structures to orbit that are larger than the packaging envelope dictated by payload fairing dimensions. If this constraint were removed, larger telescopes would enable higher resolution for science and surveillance in space.

TABLE OF CONTENTS

1. INTRODUCTION	1
2. FAIR-DART REFERENCE DESIGN.....	2
3. EXAMPLE ASSEMBLY SEQUENCES	4
4. HUMAN AND ROBOTIC ASSEMBLY TECHNIQUES.....	4
5. END-MEMBER ASSEMBLY SCENARIOS.....	6
6. KEY HUMAN-ROBOTIC TRADE SPACE METRICS	7
7. ENABLING TECHNOLOGY AND INFRASTRUCTURE ...	9
8. CONCLUSIONS	10
REFERENCES	10
AUTHOR BIOGRAPHIES	11
ACKNOWLEDGMENTS	11

1. INTRODUCTION

Need for In-Space Telescope Assembly

With the completion of NASA's Great Observatories suite of space-based telescopes, a wide range of the electromagnetic spectrum has been covered, from infrared to gamma rays. As our knowledge of the universe has improved, astronomical research has tended toward seeking answers to

The straightforward solution to the size limit of space optics is to shift the paradigm of integration and testing to allow these processes to be conducted in the low gravity environment of space. With such a shift, a robotically-deployed telescope of almost any size can have its performance verified reliably. But once the step of in-space integration and testing is taken, one might as well consider the trade between robotic deployment and human assembly. Studies [e.g., 1] have shown that, for a given shroud size, a much larger aperture can result from a human-assembled system when compared to a robotically-deployed system. This is because volume and mass are not being taken up by deployment systems. Additionally, a human-assembled system affords significantly reduced system complexity when compared with a robotically deployed system. Space-based assembly allows the complete system to be constructed, aligned, and checked out after the launch trajectory is complete and the components are in a stable, very weak gravitational environment. It also allows optical elements that can be assembled from smaller, much lighter components and adjusted to ensure optimal imaging. Finally, it allows the primary structure to be assembled from a simply-packaged kit of standard rods and connecting interfaces.

Post-assembly alignment and adjustment further enhance the value of space-based assembly. The designer does not have to ensure dimensional stability after final ground-based qualification testing, only that the final configuration is achievable on orbit. This should greatly reduce the mass of the system. The ability to make changes in space also demonstrates several other very desirable features. With the use of automated systems, telerobotics, or astronaut extravehicular activity (EVA), a space instrument assembly can be repaired, maintained, and upgraded. This means the assembly can recover from repairable failures after launch, either before it becomes operational or years after initial operations. Hubble Space Telescope (HST) provides an excellent example of the value of space-based repair and maintenance: through corrections to a faulty primary lens, replacement of solar arrays that were flexing in response to thermal oscillations during the day-night cycle, replacement of damaged gyroscopes, and replacement of solid nitrogen coolant.

Current State of the Art for Space-Based Assembly

There have been three significant examples to date of space-based assembly. A prototype space station truss assembly (ACCESS) [2] was assembled by EVA astronauts aboard a Space Shuttle flight in 1985. While not originally assembled in space, HST has shown repeatedly the value of in-space repair and maintenance since the first corrective lens insertion in 1993. The International Space Station (ISS) is already the largest structure ever assembled in space, and it continues to grow as it approaches Assembly Complete.

Fully-Assembled vs. Human-Enabled vs. Machine-Enabled

Experience with HST has demonstrated the value of human participation in the repair and maintenance of a space-based telescope. With current technology, EVA operations are limited to Space Shuttle-compatible orbits, i.e., less than 800 km altitude and less than 57 degrees inclination. Long-range NASA planning considers the possibility of establishing human-tended infrastructure at a base, known as the Gateway, in the vicinity of the Earth-Moon L1 libration point. This would allow EVA operations to extend well beyond geostationary orbits. The systems trades among ground-based assembly, EVA assembly, or robotic assembly then hinge on other factors, such as total cost vs. success probability, safety restrictions based on astronaut presence, environmental concerns such as propulsion for free-flying astronauts or robots, and telerobotic or autonomous robotic technology readiness and risk.

Preview of Sections to Follow

In the following sections, this paper addresses metrics to support analysis of which space-based assembly techniques to consider in assembling large space telescopes. Section 2 describes a reference design for a large, infrared telescope assembled at the Gateway location. Section 3 describes potential assembly sequences for the reference design, while Section 4 describes the range of human and robotic techniques to be considered in performing trade study analyses.

A discussion of end-member assembly scenarios is presented in Section 5, and key trade-space metrics in Section 6 allow assessment of the optimum mix of human and robotic techniques. To support an accurate evaluation and application of these techniques, this paper wraps up with a summary of enabling technology and infrastructure in Section 7, and the authors' conclusions in Section 8.

2. FAIR-DART REFERENCE DESIGN

Need for a Reference Design

The FAIR-DART space-telescope design offers a basis for defining an example in-space assembly sequence. Its use as a reference design also provides the opportunity to define a decision tree and key metrics for choosing among more refined assembly options, and to identify major infrastructure assumptions and technology requirements for in-space telescope assembly.

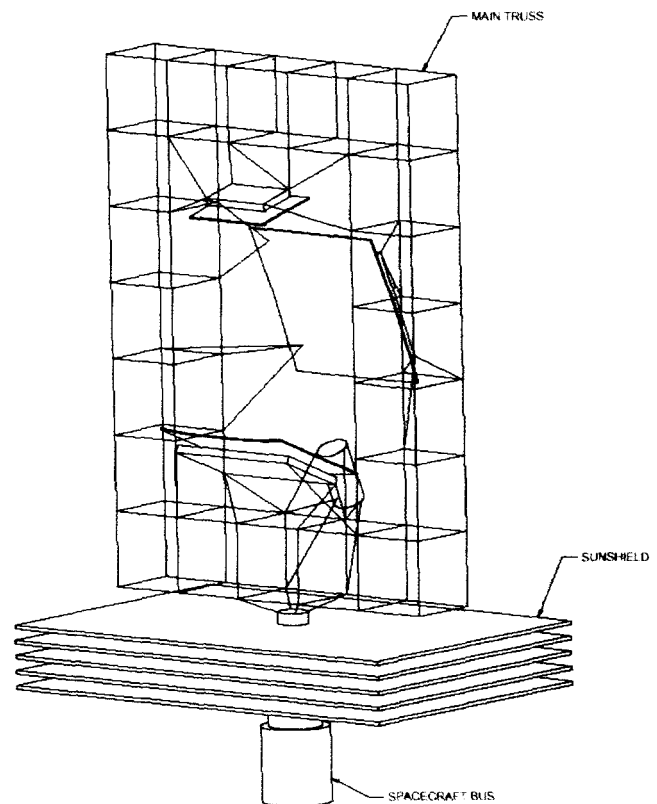


Figure 1. FAIR-DART Design

History of FAIR-DART Concept

The FAIR-DART concept is for a mission to deploy a 10-m equivalent telescope at the Earth-Moon L1 libration point and operate it for five years at Sun-Earth L2 during the mid-to-late next decade (FAIR = Filled Aperture InfraRed Telescope, DART = Dual Anamorphic Reflecting Telescope). The rationale for the concept is based on science objectives that can be achieved only by a post-NGST (Next Generation Space Telescope, recently renamed for James Webb), large-aperture far-infrared and sub-millimeter space telescope. In

this optical wavelength region, telescopes can study the behavior of interstellar gas and dust over a wide range of redshifts, providing insight into processes inside stars, molecular clouds, and galaxies. FAIR-DART was studied by JPL's Team X (Advanced Projects Design Team, including Stuart Stephens) during several half-day design sessions in early

2002, with the objectives of evaluating feasibility, identifying critical assumptions, and estimating equipment, mass, and cost requirements [3]. A drawing [4] is provided in Figure 1, showing telescope mirrors, supporting truss structure, sunshade, and spacecraft bus, and the basic features of the design are listed in Table 1.

Table 1. Characteristics of FAIR-DART Design*

Science: better understand the origin and evolution of the universe and its galaxies, stars, and planets
Telescope: 10-m equivalent: FAIR = Filled Aperture InfraRed Telescope, DART = Dual Anamorphic Reflecting Telescope
Spectral Range: high spatial and spectral resolution imaging in the 40-500 micron spectral range
Rationale: science can be achieved only by a post-NGST telescope, and by technologies needed to exploit this spectral range
Launch: circa 2014 on a Delta 4450 for insertion at the EM L1 libration point**
Trajectory: to EM L1 via SE L1 (saves delta-V but takes months), then on to the operational orbit at SE L2
Assembly, Deployment, and Checkout: construction takes place using a manned Gateway operations facility at EM L1
Operations: after checkout, the telescope is transferred to a SE L2 Lissajous orbit, where it is intended to operate for 5 years
Servicing: for this early study, the spacecraft and instruments are not designed with the intent to be serviceable
Instruments: infrared and far-infrared cameras as well as an infrared spectrometer, with detectors actively cooled to ≤ 6 K
Optics: baselined as a system of thin-film reflectors based on innovative new technology developments
Structure: a large truss structure is assembled and deployed at the Gateway to support the thin-film reflectors
Thermal Control: a multi-layer V-groove sunshade system provides passive cooling of the telescope to 10 K
Attitude Control: spacecraft is 3-axis stabilized to provide pointing control with reaction wheels and cold gas thrusters
Propulsion: system also uses hydrazine for EM L1 orbit insertion delta-V and orbit maintenance prior to optics deployment
Power: spacecraft and telescope power is provided by a fixed, deployable solar array
Telecommunications: high-rate Ka-band downlink with a gimbaled HGA to 11-m commercial or 12-m DSN ground stations
Technology: TRL 6 technology cutoff occurs in 2009-2010 for a 2014 launch

* 2002, JPL Team X (Advanced Projects Design Team) with representatives from NASA HQ, LaRC, JSC, and GSFC

** EM L1/L2 = Earth-Moon libration points, and SE L1/L2 = Sun-Earth libration points

FAIR-DART Design Requirements

FAIR-DART has been investigated as a candidate for space-based assembly. Due to the size of the three large reflectors, it would not be practical to launch it fully assembled. The telescope optics were baselined as a system of thin-film reflectors and science instruments supported by a large truss structure. A multi-layer V-groove sunshade passively cools the telescope, and is attached to a spacecraft bus from which all of these are deployed. The spacecraft bus fits on a Delta 4450 launch vehicle in a 5-m fairing. It is 3-axis stabilized for fine pointing control during operations using reaction wheels and cold gas thrusters to avoid contamination. The propulsion system also uses hydrazine for delta-V and orbit maintenance maneuvers. A fixed, deployable solar array provides power. High-rate data are downlinked at Ka-band with a gimbaled HGA. Instrumentation consists of infrared and far-infrared cameras and an infrared spectrometer, with actively cooled detectors. The cutoff date for technology development to TRL 6 is in 2009-2010 for a 2014 launch.

FAIR-DART Options: Shuttle, ISS, and Gateway

The Team X FAIR-DART concept was initially studied assuming assembly in Low Earth Orbit (LEO), at the Space Shuttle or ISS. However, the early 2002 option features assembly at the Gateway facility, a human-accessible operations facility at Earth-Moon L1. In 2014, FAIR-DART launches to the Gateway for assembly, deployment, and checkout operations. A baseline timeline calls for saving

delta-V by traveling first to Sun-Earth L1 before arriving at Earth-Moon L1, taking 9-10 months enroute. A year later, the telescope is sent, without humans, to its 5-year operational orbit at Sun-Earth L2.

Gateway Infrastructure Concept

The Gateway concept [5] consists of infrastructure at Earth-Moon L1 supporting multiple NASA exploration goals beyond LEO. A Gateway has several advantages in case humans are important for supporting a major in-space science facility: (1) after construction, a telescope or other facility may be transferred to the Earth-Sun libration points or elsewhere with very modest delta-V [6]; (2) humans may return to Earth relatively quickly in case of emergency; (3) long-term habitation at this site may be supported relatively easily from Earth; and (4) capabilities may be developed at this site for longer-term, deep-space operations while still within short travel-time of Earth. The Gateway is envisioned as intermittently staffed for roughly a month at a time, with crews of about four people, life support systems, and tools to support in-space construction. Separate transportation is needed to and from the Gateway. Assembly and other construction work is performed on a platform at the Gateway or at a standoff distance still in close proximity to the facility.

FAIR-DART Assembly, Deployment, and Checkout Tasks

The Team X timeline for FAIR-DART activities includes a roughly 6-month interval at Earth-Moon L1. Events in that

time include rendezvous with the Gateway and safing of the spacecraft, assembly of the telescope and truss structural elements, mirror deployment and testing of the telescope, and finally a window for human revisit if necessary while still in the vicinity of the Gateway. This timeline for assembly, deployment, and checkout is not very detailed. A 25-by-35-m deployable truss option that was considered in the Team X study consists of 5-m truss elements; human EVA is used to assist in the deployment and assembly of the structure. Mirror deployment occurs separately, with care taken to avoid contamination, and final checkout and testing are done last.

FAIR-DART Assembly Options and Trade Space

Assembly options considered in the Team X study include the following. Deployment at Sun-Earth L2 was rejected in favor of deployment and checkout at the Earth-Moon L1 Gateway in order to have humans nearby while still avoiding contamination as much as possible. Inflatable structural elements were considered for the telescope truss, but not investigated in detail. Thin-film reflectors were baselined in this concept, although other options are possible for the telescope optics. Most importantly, the mix of human and robotic involvement in the various assembly tasks was not explored in detail; humans were assumed to be available at the Gateway, with telerobotic tools to aid them.

FAIR-DART Technology and Infrastructure Assumptions

Important technology and infrastructure assumptions for the Team X FAIR-DART design include: (1) the telescope is launched on an expendable launch vehicle (ELV); (2) an assembly crew is available at an Earth-Moon L1 Gateway facility; (3) only one telescope is built and one assembly opportunity is available; (4) the truss and sunshade are partly pre-assembled while the spacecraft bus is mostly preassembled; and (5) contamination of telescope optics is a major issue.

3. EXAMPLE ASSEMBLY SEQUENCE

Range of Possible Assembly Sequences

A previous paper [7] classified the space telescope assembly trade space and the range of choices for human and robotic involvement by considering a decision matrix with branch points for launch vehicle, assembly location, types of human and robotic assembly and servicing, and options for transportation and checkout. For example, in one scenario: (a) the observatory is packaged into a single launch vehicle for initial assembly at ISS in LEO, (b) the launch vehicle payload includes a transfer stage to carry the assembled observatory to its operational orbit at Sun-Earth L2, and (c) regular servicing is performed by temporarily returning the telescope to Earth-Moon L1. In this case, a high-level transportation, assembly, checkout, and servicing sequence, and the range of options considered, are shown in Table 2.

Present Approach to Robotic and Human Emphasis

In this paper, the approach taken is: (a) start with the FAIR-DART reference design, (b) select a baseline transportation,

assembly, checkout, and servicing sequence, (c) map this sequence into a decision matrix of options similar to the ones considered previously, (d) focus on telescope assembly and construct a high-level timeline of tasks without yet choosing specific techniques to accomplish the tasks, and (e) consider various scenarios for robotic and human involvement. This baseline sequence (steps a-d) is shown in Table 3. In this sequence, the telescope and trajectory are based on the FAIR-DART design, the telescope is launched on an ELV to a manned Gateway facility at Earth-Moon L1, and the operating telescope remains at Sun-Earth L2 where no servicing is performed except for orbit maintenance. This baseline sequence provides a basis for examining two end-member telescope assembly scenarios: one conducted mainly robotically, and one with liberal use of human EVA.

Assembly Sequence Features that Lead to the Use of Metrics

This baseline sequence of transportation, assembly, checkout, and servicing events suggests several classes of metrics that may be useful to consider in deciding among human and robotic techniques for in-space construction. At first glance, Table 3 includes discriminators related to launch and orbit transfer, rendezvous and inspection, assembly and test in the vicinity of a servicing spacecraft, and deployment and test at a standoff distance from a servicing spacecraft. Clearly, schedule and cost are also important. The assembly and checkout steps suggest discriminators involving precision of task definition, accessibility, availability of tools, and contamination. Also, implicit in any decision about whether to use humans or robots will be assessments of risk and the quality of the assembled product.

4. HUMAN AND ROBOTIC ASSEMBLY TECHNIQUES

Robotic Assembly Techniques Applied to Reference Design

The robotic assembly techniques considered in this paper cover a wide range in terms of the amount of human supervision involved. At one end of the spectrum, fully autonomous robots will eventually be qualified to work in space programmed with their own decision-making capability. A step away from fully autonomous robots are machines that come scripted with stored sequences of commands, such as many deployment mechanisms or robotic Earth-orbiting and interplanetary spacecraft. Additional robotic assembly techniques require human involvement on the ground: either ground-in-the-loop communications prior to on-site robotic execution of stored commands, or telerobotic action at a distance via remote human control (i.e., real-time commands). Another robotic technique that also requires human involvement is a variation of the last mode, and has often been used in recent years for Space Shuttle and ISS operations, namely telerobotic assembly via local human control from inside a spacecraft (IVA). These techniques, and others considered for human assembly, are listed in Table 4.

Human Assembly Techniques Applied to Reference Design

The spectrum of in-space assembly techniques considered in this paper that require human involvement begins with some

Table 2. Previous Approach [7]: Example Sequence of Assembly Events

Step	Description	Options (example choices in bold)
1	Package observatory into launch vehicle	α. ELV β. Space Shuttle
2	Launch into ISS orbit	x. Crew comes from ISS or later Shuttle flight y. Crew launches with observatory
3	Assemble observatory in LEO	A. Fully autonomous robotic assembly B. Automated assembly with crew backup C. Teleoperated assembly D. EVA assembly
4	Check out observatory in LEO and repair/adjust as required	
5	Transfer observatory from LEO to SE L2	
6	Check out observatory and operate at SE L2	
7	Transfer observatory from SE L2 to EM L1 for maintenance	
8	Service observatory at EM L1	A. Fully autonomous robotic servicing B. Automated servicing with crew backup C. Teleoperated servicing D. EVA servicing
9	Transfer observatory from EM L1 to SE L2	

Table 3. Present Approach: Baseline Sequence of Assembly Events and High-Level Timeline

Step	Description (days after launch in brackets)	Options (baseline choices in bold)
1	Package observatory into launch vehicle	α. ELV
	Integrate and test ELV and payload at launch site	β. Reusable manned launch and transfer vehicle
2	Launch to EM L1 (9-10 months via SE L1 and EM L2)	x. Crew is available at EM L1 Gateway facility
	Launch and perform post-departure maneuver {0-1}	y. Crew launches with observatory
	Coast near SE L1 {30-240}	
	Perform EM L1 orbit insertion {285}	
3	Assemble observatory at EM L1	A. Fully autonomous robotic assembly
	Rendezvous and safe spacecraft {285-291}	B. Automated assembly with crew backup
	Rendezvous telescope with Gateway	C. Teleoperated assembly
	Safe spacecraft carrying telescope	D. EVA assembly
	Assemble and test telescope near Gateway {291-345}	[choices were subject to trade in this paper]
	Gather parts of telescope	
	Assemble telescope structure and truss	
	Assemble telescope subsystems and instruments	
	Contingency	
	Test telescope subsystems and instruments	
	Contingency	
4	Check out observatory at EM L1 and repair/adjust as required	A. Fully autonomous robotic checkout
	Deploy mirrors and test telescope {345-415}	B. Automated checkout with crew backup
	Maneuver telescope away from Gateway (or vice-versa)	C. Teleoperated checkout
	Deploy mirrors and cool optics	D. EVA checkout
	Test telescope	[choices were subject to trade in this paper]
	Window for human revisit for repairs if needed {415-465}	
	Maneuver telescope back to Gateway (or vice-versa)	
	Contingency	
	Maneuver telescope away from Gateway (or vice-versa)	
5	Transfer observatory from EM L1 to SE L2	
	Perform SE L2 injection maneuver {465}	
6	Check out observatory and operate at SE L2	
	Arrive at SE L2 Lissajous orbit {555}	
	Perform science operations (5 years) {585-2400}	
7	Service observatory at SE L2	A. Fully autonomous robotic servicing
	Perform orbit maintenance maneuvers {every 45 days}	B. Automated servicing with crew backup
		C. Teleoperated servicing
		D. EVA servicing

Table 4. Assembly Techniques Considered in This Paper

1. Robotic: Fully autonomous decision-making
2. Robotic: Scripted with a stored sequence of commands
3. Robotic: Ground-in-the-loop
4. Telerobotic: Remote human control
5. Telerobotic: Local human control (IVA)
6. Human: Other astronaut IVA in support of assembly
7. Human: Astronaut EVA to supervise robotic assembly
8. Human: Astronaut EVA to supervise telerobotic assembly
9. Human: Astronaut EVA to perform assembly

of the robotic techniques considered above. Actually, humans are always involved since they are required for programming even fully autonomous machines and for scripting the commands or sending the real-time commands required for ground-in-the-loop or telerobotic techniques. In-space human involvement is required beginning with telerobotic techniques driven by local human control, i.e., IVA. Additional human involvement is possible in the range of modes shown in Table 4. Human IVA from inside a spacecraft in support of in-space assembly, either by robots or humans, is a possibility (e.g., organization of telescope parts or transportation of the completed telescope). Additionally, there is a spectrum of astronaut EVA options, from those done for the purpose of supervising robotic or telerobotic assembly to those in which hands-on astronaut assembly is the whole idea.

5. END-MEMBER ASSEMBLY SCENARIOS

Rationale for End-Member Assembly Scenarios

Our baseline sequence provides a basis for examining two end-member telescope assembly scenarios: one conducted mainly robotically, and one with liberal use of EVA. Details were added to the baseline sequence of events shown in Table 3 for those steps involving assembly and checkout at the Gateway facility, and a more detailed timeline was associated with this sequence. Two end-member scenarios were then listed with the assembly techniques that seemed most appropriate to the two cases. All of this was done in preference to trying to describe a full spectrum of cases spanning the range of human and robotic assembly techniques. Another factor motivating the use of end-member scenarios was the observation that, once human EVA is introduced into one step in a scenario, it often becomes less expensive to use it for additional steps, and while it may not be the cheapest option it is often the least risky option. Similarly, the mainly robotic end-member case was considered because there appears to be a step-function entry barrier to using EVA in the first place, and there is considerable motivation, in terms of cost and risk, for considering a case that is free from direct human in-space involvement altogether.

Scenario A: Spare Use of Humans

Table 5 summarizes the steps in the baseline assembly sequence and the human and robotic assembly techniques that are likely to be used in each scenario. In scenario A, the as-

sembly technique for a given step is evaluated assuming all other assembly steps are performed robotically. In this case, many steps in the assembly sequence may be capable of being fully automated (technique 1), e.g., rendezvous and safing the spacecraft carrying the telescope, gathering parts of the telescope, some aspects of assembly itself, many aspects of testing the telescope subsystems and instruments, maneuvering the assembled telescopes, and deployment of mirrors and testing of the fully configured telescope. However, in the foreseeable future, some steps are likely to need a more deterministic sequencing of events (techniques 2 or 3), e.g., pre-scripting with stored command sequences or ground-in-the-loop with stored command sequences. Such steps include many aspects of the actual assembly, e.g., final (precise) positioning of the telescope structure, and assembly of instruments, optics, and undeployed mirrors. The only steps in the assembly sequence that are likely to require telerobotic or direct human involvement are those set aside for contingency activities, in which case any of the human techniques listed above are possible (techniques 4 through 9).

Table 5. Cases A and B: Descriptive Scenarios

Scenario A: Spare Use of Humans
<i>Candidates for technique 1 (or techniques 2 or 3):</i>
Rendezvous and safing of the spacecraft with the Gateway
Gathering parts of the telescope
Assembly of most of the telescope structure and truss, and deployment of any deployable spacecraft bus subsystems
Testing the telescope subsystems and instruments
Maneuvering the assembled telescope
Mirror deployment and testing of the configured telescope
<i>Candidates for techniques 2 or 3:</i>
Final assembly and positioning of the telescope structure
Assembly of instruments, optics, and undeployed mirrors
<i>Candidates for techniques 4 through 9:</i>
Contingency activities (following assembly, preliminary checkout, mirror deployment, and final testing)
Scenario B: Liberal Use of Humans
<i>Candidates for techniques 2 through 4 (or technique 5)</i>
Rendezvous of the spacecraft with the Gateway
Power-on and checkout of spacecraft bus subsystems and instruments
Maneuvering the assembled telescope
Mirror deployment and testing of the configured telescope
<i>Candidates for technique 5:</i>
Safing of the spacecraft carrying the telescope
Gathering parts of the telescope (or technique 6)
Inspection of the telescope
<i>Candidates for techniques 6 through 8 (or technique 9)</i>
Assembly of most of the telescope structure and truss, and deployment of any deployable spacecraft bus subsystems
Assembly of telescope optics and undeployed mirrors
Contingency activities (following assembly, preliminary checkout, mirror deployment, and final testing)
<i>Candidates for technique 9:</i>
Final assembly and positioning of the telescope structure
Assembly of the instrument structure and instruments

Scenario B: Liberal Use of Humans

In scenario B, the assembly technique for a given step is evaluated as if EVA is easily available and is used for other steps. In this case, there are only a few steps in the assembly sequence that are more practical (or less risky and costly) without direct human involvement (techniques 2 through 4); these include rendezvous with the Gateway, power-on and checkout of the spacecraft bus subsystems and instruments, maneuvering the assembled telescope, and mirror deployment and testing of the fully configured telescope. These steps could also be done telerobotically with local human control (technique 5), which would be the preferred mode for some additional steps: safing of the spacecraft carrying the telescope, gathering parts of the telescope (some of this could be done with IVA, technique 6), and inspection of the telescope. Candidates for direct human involvement involvement short of EVA to perform assembly (techniques 6 through 8) include assembly of most of the telescope structure and truss, deployment of any deployable spacecraft bus subsystems, assembly of telescope optics and undeployed mirrors, and contingency activities. Finally, the steps which would mostly likely utilize human EVA to perform assembly directly (technique 9) are final assembly and positioning of the telescope structure, and assembly of the instrument structure and instruments themselves.

Discussion

Table 6 represents the baseline sequence of assembly events filled out to a sufficient level of detail to allow us to decide which assembly techniques can be applied at which steps in the process. The FAIR-DART-derived sequence and high-level timeline in Table 3 was used as a starting point, and a Team X timeline was used for guidance, but the techniques assigned to the assembly steps were chosen based on the set of human and robotic assembly techniques and the logic described above.

Only the assembly and checkout portions of the timeline are filled out in detail. The assembly techniques (1 through 9) are listed for Case A (sparse use of humans) and Case B (liberal use of humans).

6. KEY HUMAN-ROBOTIC TRADE SPACE METRICS

Development of Metrics

The debate over the favored mix of robotic vs. human-assisted space operations has continued ever since the Apollo program precursors. On one hand, human intelligence and dexterity favor EVA operations for complex tasks for which a clear mechanical detail flow is not available, for which the exact nature of the repair is unknown, or for a large number of similar tasks for which expert judgment is needed. On the other hand, robotic involvement is favored for carefully planned operations with straightforward mechanical dexterity and available tools for operations and hold-down procedures, or when operations are to be performed in locations inaccessible to humans. Furthermore, the cost of human space missions and their necessary support infrastructure is

much greater than the cost of small spacecraft delivery. A study of the optimum approach to in-space assembly and servicing dictates a serious attempt at defining metrics with which to evaluate alternative operations concepts.

Transportation

A preliminary listing of discriminators is shown in Table 7. The first element relates to accessibility of the servicing location, which is listed here as transportation. If the location is inaccessible to humans, e.g., due to being in a high-radiation environment or in a location not expected to be accessible in the reasonable future (e.g., more than 1,000,000 km from Earth), then robotic operations are greatly favored.

Mission Costs

Cost of the mission is clearly a significant metric for selecting optimum operations concepts. This should include costs for full operations, including ground operations, servicing vehicle and tools, transportation, and maintenance of vehicles, tools, and systems in space. This should also include costs of designing, testing, and building tools, as well as any storage costs, especially if the vehicle or the tools need in-space storage.

Precision of Task Definition

Sensitivity of the task to anomalies will have a strong influence on the degree to which autonomy is favored over human involvement. If the entire task is precise and there is minimal risk of misaligned, misplaced, or damaged components, then autonomy might be in order. If this risk is high, then human flexibility might be favored.

Accessibility and Availability of Tools

Related to this risk is the access to the components to be assembled: Are the connections easy to access? Does the operation require reasonable dexterity or flexibility? An additional sensitivity factor is the availability of required tools: Are the tools already in place? Must they be launched? Must they first be designed and tested? Is the technology ready?

Environmental Controls

Assembly of optical elements for space-based telescopes might be sensitive to contamination. This contamination might result from either outgassing of the servicing vehicle or spacesuit, or from propulsion for on-site maneuvering.

Summary

Key discriminators for assessing the relative merits of varying levels of autonomy appear to include availability of transportation, certainty of the required assembly operations, and total mission costs. The favored procedure varies as these discriminators vary. As the technology for telescope assembly matures, additional metrics will develop for performing trade studies.

Table 6. End-Member Telescope Assembly Scenarios (Techniques for Cases A and B): Task Sequence and Timeline

Sequence of tasks (days after launch in brackets)	Timeline (days)	A Technique	B Technique
1. Package observatory into launch vehicle	< 0		
<u>Integrate and test ELV and payload at launch site</u>			
2. Launch to EM L1 (9-10 months via SE L1 and EM L2)	0-285		
<u>Launch</u>	<u>0</u>		
<u>Perform post-departure maneuver</u>	<u>1</u>		
<u>Coast near SE L1</u>	<u>30-240</u>		
<u>Perform EM L1 orbit insertion</u>	<u>285</u>		
3. Assemble observatory at EM L1	285-345		
3.1 Rendezvous and safe spacecraft	285-291		
3.1.1 Rendezvous telescope with Gateway	285-286		
3.1.1.1 Rendezvous at EM L1 {1}	285-286	123	2345
3.1.2 Safe spacecraft carrying telescope {5}	286-291		
3.1.2.1 Inspect spacecraft carrying telescope {2}	286	123	5
3.1.2.2 Safe spacecraft and telescope, turn power off {1}	288	123	5
3.1.2.3 Remove telescope from spacecraft, prepare for assembly {1}	289	123	5
3.1.2.4 Put spacecraft in a safe location {1}	290	123	5
3.2 Assemble and test telescope near Gateway	291-345		
3.2.1 Gather parts of telescope {2}	291-293		
3.2.1.1 Remove parts of telescope from package {1}	291	123	5
3.2.1.2 Organize parts in logical arrangement for assembly {0.5}	292	123	5
3.2.1.3 Prepare tools from Gateway to be used in assembly {0.5}	292	123	56
3.2.2 Assemble telescope structure and truss {10}	293-303		
3.2.2.1 Assemble spacecraft bus, sunshield, truss attach point {1}	293	123	56789
3.2.2.2 Assemble and pre-position four main truss sections {4}	294-298	123	56789
3.2.2.3 Finalize assembly and positioning of telescope structure {4}	298-302	23	9
3.2.2.4 Assemble attach points for mirrors, optics, instruments {1}	302	123	56789
3.2.3 Assemble telescope subsystems and instruments {7}	303-310		
3.2.3.1 Assemble, deploy deployable spacecraft bus subsystems {1}	303	123	56789
3.2.3.2 Assemble instrument structure and instruments {2}	304-306	23	9
3.2.3.3 Assemble optics structure and optics {2}	306-308	23	56789
3.2.3.4 Assemble mirror structure and (undeployed) mirrors {2}	308-310	23	56789
3.2.4 Contingency {8}	310-318	23456789	56789
3.2.5 Test telescope subsystems and instruments {17}	318-335		
3.2.5.1 Inspect unpowered telescope {2}	318-320	123	5
3.2.5.2 Power on spacecraft bus subsystems, then instruments {2}	320-322	123	2345
3.2.5.3 Check out spacecraft bus subsystems {5}	322-327	123	2345
3.2.5.4 Check out instruments (optics/mirrors to extent possible) {6}	327-333	123	2345
3.2.5.5 Inspect powered telescope {2}	333-335	123	5
3.2.6 Contingency {10}	335-345	23456789	56789
4. Check out observatory at EM L1 and repair/adjust as required	345-465		
4.1 Deploy mirrors and test telescope	345-415		
4.1.1 Maneuver away from Gateway (or vice-versa) {2}	345-347	123	2345
4.1.2 Deploy mirrors {3}	347-350	123	2345
4.1.3 Cool optics {25}	350-375	123	2345
4.1.4 Test telescope {40}	375-415	123	2345
4.2 Window for human revisit for repairs if needed	415-465		
4.2.1 Maneuver back to Gateway (or vice-versa) {3}	415-418	123	2345
4.2.2 Contingency {45}	418-463	23456789	56789
4.2.3 Maneuver away from Gateway (or vice-versa) {2}	463-465	123	2345
5. Transfer observatory from EM L1 to SE L2	465-555		
<u>Perform SE L2 injection maneuver</u>	<u>465</u>		
6. Check out observatory and operate at SE L2	555-2400		
<u>Arrive at SE L2 Lissajous orbit</u>	<u>555</u>		
<u>Perform science operations (5 years)</u>	<u>585-2400</u>		
7. Service observatory at SE L2	every 45 days		
<u>Perform orbit maintenance maneuvers</u>			

Table 7. Metrics as Applied to Assembly Techniques

Feature	Metric
Transportation	Available of transport vehicles Ability of transport vehicles to carry sufficient payload
Mission costs	Transportation costs Service vehicle costs Toolkit design, fabrication, and storage costs Preflight planning costs Ground operations costs
Precision of task definition	Certainty of precise task procedures Risk of misinformation related to component placement, dimensions, required torque, etc.
Accessibility	Accessibility of parts Required flexibility, dexterity
Availability of tools	Tools designed and on-orbit
Environmental controls	Sensitivity to environment Servicer environmental release

7. ENABLING TECHNOLOGY AND INFRASTRUCTURE

Technology Needs

Although there is a major experience base with EVA servicing of HST and with satellite rendezvous, capture, and repair, there has not yet been any demonstration of robotic in-space assembly or servicing. The technologies are not yet available for robotic servicing, and telescopes have yet been assembled in space. Required technologies are different for human and robotic assembly techniques. They fall generally into six categories: (1) transportation to the assembly/servicing location; (2) rendezvous, docking, and berthing with the platform to be serviced (the client platform); (3) communications among the servicer, the client platform, and a ground crew (or space-based crew); (4) logistics for storage of tools and replacement parts; and (5) tools for the positioning, support, removal, and installation of components. Table 8 is a brief summary of infrastructure requirements.

Transportation and Rendezvous

For human missions to LEO, the Space Shuttle is the preferred transportation for the foreseeable future. Crew-assisted servicing or assembly in Shuttle-compatible orbits will be performed either directly from the Space Shuttle, or at ISS — either attached to or in the vicinity of ISS. For servicing operations in higher locations, either at the Gateway or beyond, such as at the Sun-Earth L2 operating location, human missions will require additional piloted transportation, and a habitable base for operations. The transportation might include reusable Orbital Transfer Vehicles (OTVs) based at ISS, or new upper stages for a human-rated launch vehicle, while an operational habitable base at the Gateway is necessary for long-term crew support. All human missions require a safe, reliable method for the crew to return to Earth, under normal and emergency conditions.

Robotic operations will also require some form of routine transportation to the servicing location. For the initial placement, conventional launch vehicles are probably sufficient. Initial placement refers either to the first element of a platform that is assembled through multiple launches, or to the initial launch of a reusable servicing spacecraft. This might be simply the spacecraft to be serviced with future missions, or it might be the assembly elements for in-space assembly. Later missions will require either multiple launches with a conventional launch vehicle, or a space-based reusable OTV stationed at a location suitable for long-term storage of the OTV or the required tools, fuel, and replacement equipment.

All in-space assembly and servicing requires rendezvous and capture of the spacecraft or platform to be serviced, and some form of docking or berthing to maintain a steady position. These have been demonstrated with human missions for the Space Shuttle and ISS, as well as for satellite capture and retrieval and HST. The first demonstration of robotic rendezvous and capture is scheduled for the Orbital Express mission in 2005 [8].

Communications

Communications requirements are somewhat different for humans and for robots. Human servicing will require adequate lighting for the astronauts, and frequent communications with ground control. Robotic operations are somewhat more relaxed relative to the visual spectrum and lighting, but require more precise knowledge of positioning and other visual cues. This is likely to be provided by stereoscopic cameras to benefit ground control. The robotic operations will require more continuous, wideband communications coverage to maintain adequate operations margins.

Logistics

Whether the telescope is to be built from a few well-integrated elements that are bolted together in space or from a large arrays of rods, connectors, and mirror elements, some form of storage is required. This storage is different for assembly than for servicing. For assembly, storage is required to maintain all the parts in place, in a location that is readily accessible as needed and in the proper environment. Parts identification and orientation are also very important to storage for assembly. It seems reasonable that the storage depot should be readily accessible to the crew or the servicing vehicle from the assembly site. Assembly platforms, mounting fixtures, cameras, and required tools will also be stored in orbit.

Tools

For in-space servicing, storage may be required for tools and servicing vehicles that are to be reused. This may then be in LEO even for servicing at higher locations, if a reusable OTV is available. Fuel storage will also be required for the OTV. It is assumed here that, as satellite servicing and assembly become more and more routine, an inventory

of standard tools and fixtures will gradually build up in a storage depot. The depot could be at ISS or at a Gateway location designed for assembly, servicing, and other uses. Table 8 lists a small subset of the tools that will be required

for in-space assembly and servicing. This list will evolve as the technology becomes more routine and mature. There will also be tools required for in-space test and checkout, and for optical alignment and repair.

Table 8. Key Technologies and Infrastructure

Infrastructure Phase	Human Mission Needs	Robotic Mission Needs
Transportation	Space Shuttle to LEO Piloted OTV to higher orbit Return to Earth Habitation base	Reusable OTV
Rendezvous	Rendezvous, capture, and berthing	Rendezvous, capture, and berthing
Communications	Visual cameras TDRSS or new wideband communications	Visual cues for positioning and recognizing target New wideband communications
Logistics	Space-based storage depot for servicing equipment	Space-based storage depot for servicing equipment
Tools	Work platforms Grippers Connector stowage Cutters Bolts and fasteners	Adaptable software Grippers Connector stowage Cutters Bolts and fasteners

8. CONCLUSIONS

We have tried to distinguish between in-space telescope assembly steps that can benefit from human involvement and those that can best be accomplished with robotic techniques. This has been a challenging effort ever since EVAs were first accomplished in the Gemini program [e.g., 9]. We have taken FAIR-DART as a design reference, and performed trade studies with two scenarios for assembly at the Gateway: spare use of humans and liberal use of humans.

As we investigated the risk associated with the spare use of humans, there were a number of steps which were identified as readily achievable with current or near-term robotic technologies. However, there were several steps which would benefit directly from human presence. These steps primarily involve humans in performing contingency activities following assembly. These include preliminary checkout, mirror deployment and alignment, and final testing. A key conclusion is also that, once the gulf has been crossed to involve human presence, many of the difficult robotic tasks become simpler and less risky with either direct human involvement or through use of humans in a supervisory mode.

The scenario involving liberal use of humans showed many assignments for a work crew in a supervisory role, either from within a spacecraft at the Gateway or during EVA. A human/robotic team would be most effective at assembly of most of the telescope structure and truss, optics, and undeployed mirrors, and at deployment of any of the deployable spacecraft bus subsystems. A combined team with EVA supervision would also benefit contingency activities following basic assembly. Under this scenario, final assembly and positioning of the telescope and instrument structures is best performed with EVA processes. Another key conclusion is that, if the automation of robotic tasks continues to

increase in reliability and precision, we should expect that the pure robotic end-member case will develop into a valid choice as well.

Given the initial assumption that the Gateway infrastructure exists at the Earth-Moon L1 point, with human presence available at the assembly site, there are clear advantages to using astronauts in the assembly of the telescope, both in an active assembly role and in a supervisory and recovery role. Once the infrastructure exists, it will improve the probability of success in assembling the telescope. An added feature not addressed here will be the ability to return the telescope to the Gateway site for scheduled and unscheduled maintenance and upgrades to extend the life of the facility.

While there appear to be clear advantages to assembling the telescope with human involvement, we have not performed the trade to determine whether the cost and risk of building the infrastructure is acceptable for telescope assembly as its only mission. This is left to a future analysis, with a broader scope of additional missions

REFERENCES

- [1] Ronald M. Muller, "Orbital Assembly and Servicing of a 20-Meter Diameter Space Telescope Using the International Space Station," *NGST (James Webb Space Telescope) Public Documents Web Site*, February 28, 2000.
- [2] Walter L. Heard and Judith J. Watson, "Results of the ACCESS Space Construction Shuttle Flight Experiment," *American Institute of Aeronautics and Astronautics*, AIAA 86-1186-CP, 1986.
- [3] JPL Advanced Projects Design Team (Team X), "FAIR-DART Option #2 – 2002-08 (Updated)," Rev 2.1, January 31 and February 1, 2002, updated August 2002.

[4] Personal communication, John W. Renfro and Michael A. Fruhwirth, The Boeing Company, ExtraVehicular and Crew Systems, International Space Station.

[5] Harley Thronson, James Geffre, Steven Prusha, Larry Caroff, Charles Weisbin, the JSC Advanced Design Team, and the JPL Advanced Projects Design Team, "Gateway Concepts: Thoughts on the Construction of Future Science Facilities," *Workshop on In-Space Construction and Maintenance of Complex Science Facilities*, May 21-23, 2002.

[6] Martin W. Lo and Shane D. Ross, "The Lunar L1 Gateway: Portal to the Stars and Beyond," *American Institute of Aeronautics and Astronautics*, AIAA 2001-4768, Albuquerque, 2001.

[7] Harvey J. Willenberg, Michael A. Fruhwirth, Seth D. Potter, Stephen J. Leete, and Rud V. Moe, "Site Selection and Deployment Scenarios for Servicing of Deep-Space Observatories," *IEEE Aerospace Conference Proceedings*, March 9-16, 2002.

[8] <http://www.darpa.mil/tto/PROGRAMS/astro.html>.

[9] Harvey J. Willenberg, Seth D. Potter, John W. Renfro, and Michael A. Fruhwirth, "Technology Status and Planners' Guide for In-Space Servicing," *Boeing Report PWDM02-0214*, September 30, 2002.

AUTHOR BIOGRAPHIES

Dr. Stuart K. Stephens

Intern in 2-year Mission Architect Development Program and Senior Systems Engineer at NASA's Jet Propulsion Laboratory (California Institute of Technology).



Education: B.S. and M.S. Geophysics, Ph.D. Planetary Science, California Institute of Technology.

Areas of Experience: Planetary science, deep space mission operations, orbital mechanics, systems engineering, space mission architecture.

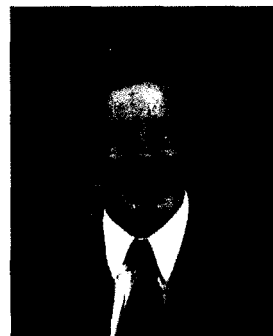
Affiliations: Division of Planetary Science of the American Astronomical Society, American Institute of Aeronautics and Astronautics.

Specific Work Experience: Intern, Mission Architect Development Program, including supporting Mission Design function for JPL Advanced Projects Design Team (Team X) and Proposal Manager for a Step 1 NASA MIDEX proposal; Science Planning Engineer, Cassini; Payload Instrument

Engineer, Mars Polar Lander; Mission Planner, Cassini; Assistant Science Coordinator, Galileo; Academic Director, Summer Science Program (high school students), Ojai, CA.

Dr. Harvey J. Willenberg

Project Manager for advanced space concepts at Boeing Phantom Works.



Education: B.S. Physics, Harvey Mudd College; M.S. Physics, M.S.E. Nuclear Engineering, and Ph.D. Nuclear Engineering, University of Washington.

Fields of Expertise: Science utilization of human space systems, advanced space mission architectures, nuclear and plasma physics.

Current Areas of Research: Concept architecture studies for Mars Sample Return, human/robotic servicing of space systems, nuclear space systems concept studies.

Affiliations: Former Vice President, Technical, of the American Astronautical Society.

Work Experience: Project Manager/Principal Investigator for multiple microgravity experiments on Mir and Space Shuttle; Chief Scientist, Space Station Freedom; leader for many advanced space concept architecture studies; formerly nuclear reactor safety engineer and designer of concepts for fusion reactors.

Personal Information: Married with three grown children, living in Menifee, California.

ACKNOWLEDGMENTS

We benefited from several useful and friendly discussions with John Renfro and Mike Fruhwirth at Boeing in Huntington Beach, and constructive feedback from Brent Sherwood at Boeing in Houston. Stuart Stephens appreciates the support of Tony Freeman and others at JPL (Caltech) and Brent Sherwood and others at Boeing in facilitating his 3-month assignment with Boeing.